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CTS ATTENUATION AND CROSS-POLARIZATION MEASUREMENTS AT 11.7 GHz

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Final Report Covering the Period 12 June 1976 - 30 August 1976
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GODDARD SPACE FLIGHT CENTER

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16. Abstract

The results of data obtained at The University of Texas at Austin during the 80 days preceding the solar eclipse shutdown on 30 August 1976 of the CTS 11.7 GHz righthand circularly polarized beacon transmitter are presented. Attenuation and cross-polarization isolation were measured. It was determined that depolarization presents a serious limitation to satellite system reliability when frequency resue by polarization diversity is employed. A 27 dB isolation margin would reduce reliability below 99.95%. For the same percentage the required fade margin was below 3 dB.

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Preface

The results of data obtained at The University of Texas at Austin during the 80 days preceding the solar eclipse shutdown on 30 August 1976 of the CTS 11.7 GHz righthand circularly polarized beacon transmitter are presented. Attenuation and cross-polarization isolation were measured. It was determined that depolarization presents a serious limitation to satellite system reliability when frequency reuse by polarization diversity is employed. A 27 dB isolation margin would reduce reliability below 99.95%. For the same percentage the required fade margin was below 3 dB.

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I. Introduction

A. General

Satellite-terrestrial communication systems depend upon the propagation of electromagnetic waves through the atmosphere. A successful design of such a system is one that meets realistic specifications. These must be based on the knowledge of any limitations introduced by the atmosphere. At millimeter wave frequencies for elevation angles above about 10° mainly two mechanisms exist that introduce limitations: (1) the absorption and reradiation of radio waves by oxygen and water vapor and (2) the absorption and scattering of radio waves by precipitation. The first can be determined by applying appropriate atmospheric models and radio sonde data (Straiton, 1975). The second causes attenuation, interference and depolarization. Attenuation and interference due to rain can be predicted if the spatial and temporal variation of rain intensity is known (Crane, 1977). The prediction of depolarization effects requires a knowledge of other parameters such as drop shape and canting angle distributions. These have not (yet) been linked to intensity to allow accurate a priori estimates.

For this purpose and in anticipation of the future need of satellite systems operating at around 12 GHz with a required reliability of 99.99 percent the Communication Technologies Satellite (CTS) includes a propagation experiment. The signal from the 11.7 GHz beacon transmitter could be used by participating experimenters for pertinent measurements.

This report describes the efforts by the Electrical Engineering Research Laboratory, The University of Texas at Austin and presents the data collected during the initial phase, from 12 June 1976 to 30 August 1976.

B. Experiment Objectives

Frequencies above 10 GHz are attractive for satellite communications because (1) they provide the opportunity for increased bandwidth as the frequencies are increased, (2) they are in a part of the spectrum where overcrowding has not yet occurred and (3) they make possible narrow beams with relatively small antennas.

Increasing attenuation does occur, however, because of the isotropic absorption of energy by water vapor and oxygen in the atmosphere and the anisotropic absorption and scattering by raindrops. To fully utilize the spectral capacity of the geosynchronous arc it has been proposed to transmit simultaneously in the same frequency band but with orthogonal polarization. This is called frequency reuse by polarization diversity.

At millimeter wave frequencies the success of this scheme is limited by two factors. One is the clear-air isolation between the two signal channels over the required bandwidth and beamwidth. The other is the depolarization caused by particles (ice or raindrops) present in the propagation path. These tend to couple energy from each signal into both channels, destroying the integrity of both messages. Thus leakage of energy from one channel to the other causes cross talk and may restrict the full use of the communication channel during rain storms. This is especially true at the microwave frequencies (10-51 GHz) where the theory predicts higher cross polarization for a given fade depth.

The objective of the research reported here was to obtain data on the attenuation and cross-polarization isolation for circular polarization due to the atmosphere at 11.7 GHz. Besides relating cross-polarization to attenuation the fraction of time that either exceeded a given level has been determined for Austin, Texas for the 80 days of measurements.

II. Receiver Description

A. Turnstile Feed

The 11.7 GHz beacon transmitter aboard CTS is nominally right hand circularly polarized (RHC). That means as the wave travels away from an observer the electric field vector rotates in a clockwise direction. In reality the beacon transmits a right hand elliptically polarized wave with an axial ratio of less than 1.5 dB anywhere within an enclosed angle of 17° centered on the electrical axis of the spacecraft antenna.

Any receiver which hopes to measure cross-polarization must therefore be able to fully couple to the transmitted signal polarization in one channel so that the other channel with orthogonal polarization receives no signal during clear air propagation. Since the cross-polarized receiver was to be able to detect a signal 45 dB below the co-polarized signal level, at least that much isolation was required from the antenna - feed point of view. A second requirement for the receiving antenna polarization arose from the fact that the exact polarization of the beacon was not known. Therefore the receiver polarization had to be adjustable after the receivers went into operation.

These requirements are met by a turnstile feed, built by us for this experiment. The turnstile is a six-port waveguide junction. It has been described by Dicke (1948) and received some attention, mainly in radar work, because it can be used as a duplexer (Crandell, 1955; Meyer et al., 1955; Fellers, 1960; McCormick, 1968). The unique property of the turnstile is that it can be adjusted to simultaneously receive any two orthogonally polarized waves with high isolation and negligible loss.

Figure 1 shows a sketch of a turnstile. The 90° intersection of two X-band waveguides results in four ports. To the center of the intersection connects a circular waveguide with its axis perpendicular to the plane formed by the rectangular guides. This represents two ports, one for each of the orthogonal waves that can be propagated down the circular guide. The radius of the circular guide is decided by its desired cutoff frequency. A match of the junction is achieved by adjustment of the penetration of three centered concentric pins. Two opposite rectangular arms have moveable shorts with remote control. The two receivers are connected to the other two rectangular arms. Isolation between these was adjusted to be greater than 55 dB with a VSWR of less than 1.06. The circular waveguide as prime focus feed was flared to put the 10 dB points of its radiation

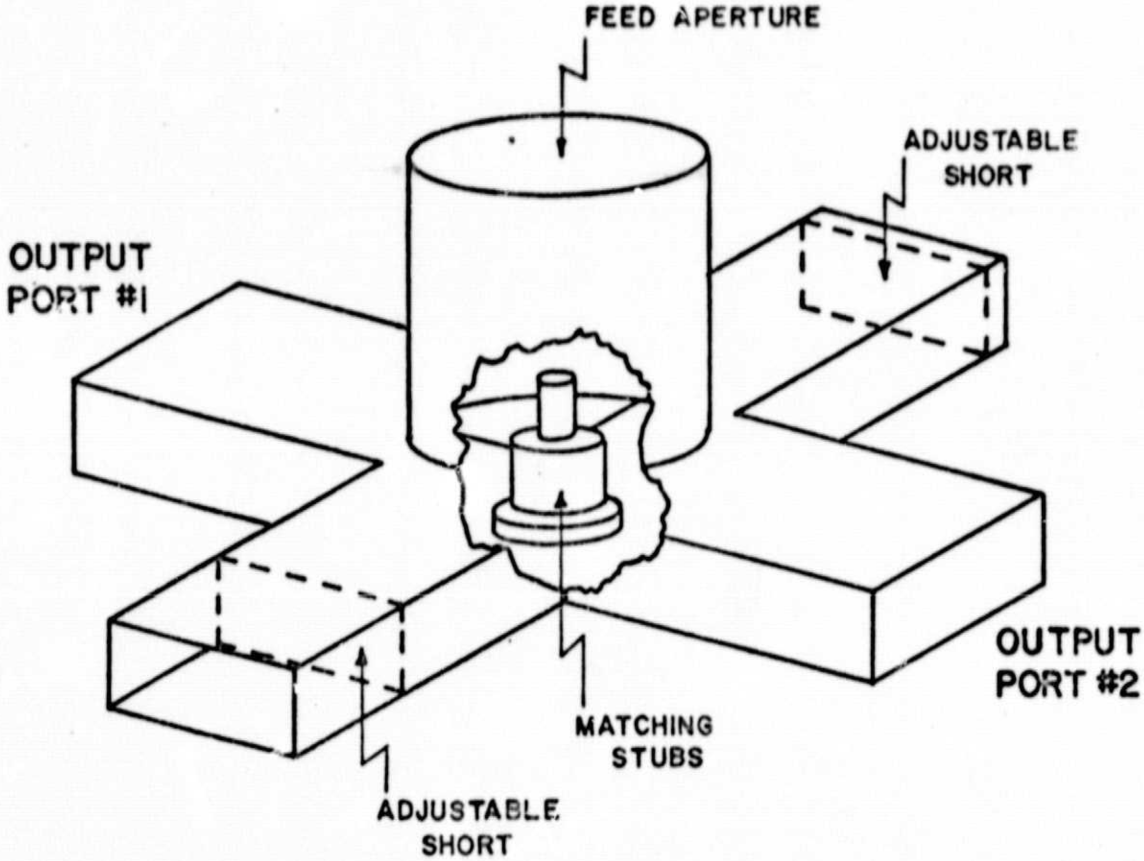

FIGURE 1 SIMPLIFIED SKETCH OF A TURNSTILE JUNCTION

pattern at the edge of the 3 m parabolic receiving antenna. The entire front end assembly can be rotated about the feed axis.

The polarization of an electromagnetic wave is defined by two numbers. Therefore two adjustments are necessary to null the signal in the cross polarized channel. Using the complex polarization coefficient (Beckmann, 1968) defined by

$$p = \frac{E^{\text{vertical}}}{E^{\text{horizontal}}} = |p| \exp\,(i \arg p)$$

all possible polarization states can be represented in the complex p plane. (See Fig. 2) It is easy to show that when the positions of the short circuits in the turnstile are adjusted (with their difference kept at $\lambda_g/4$) the two orthogonal receiver polarizations move around the unit circle. Rotating the entire receiver changes its polarization over the complex plane as indicated in Fig. 2. By proper adjustment any incoming wave polarization can be matched.

Figures 3 and 4 give the azimuth and elevation co- and cross-polarized antenna patterns measured on the CTS signal. Better than 40 dB isolation has been achieved on the electrical axis of the antenna. This isolation was maintained even after the antenna was wet with a garden hose.

B. Antenna

The beacon receiver utilizes a 3 m parabolic dish attached to an azimuth-elevation steerable converted ballistic radar mount. The pointing of the antenna is under program control with an accuracy of about .02°.

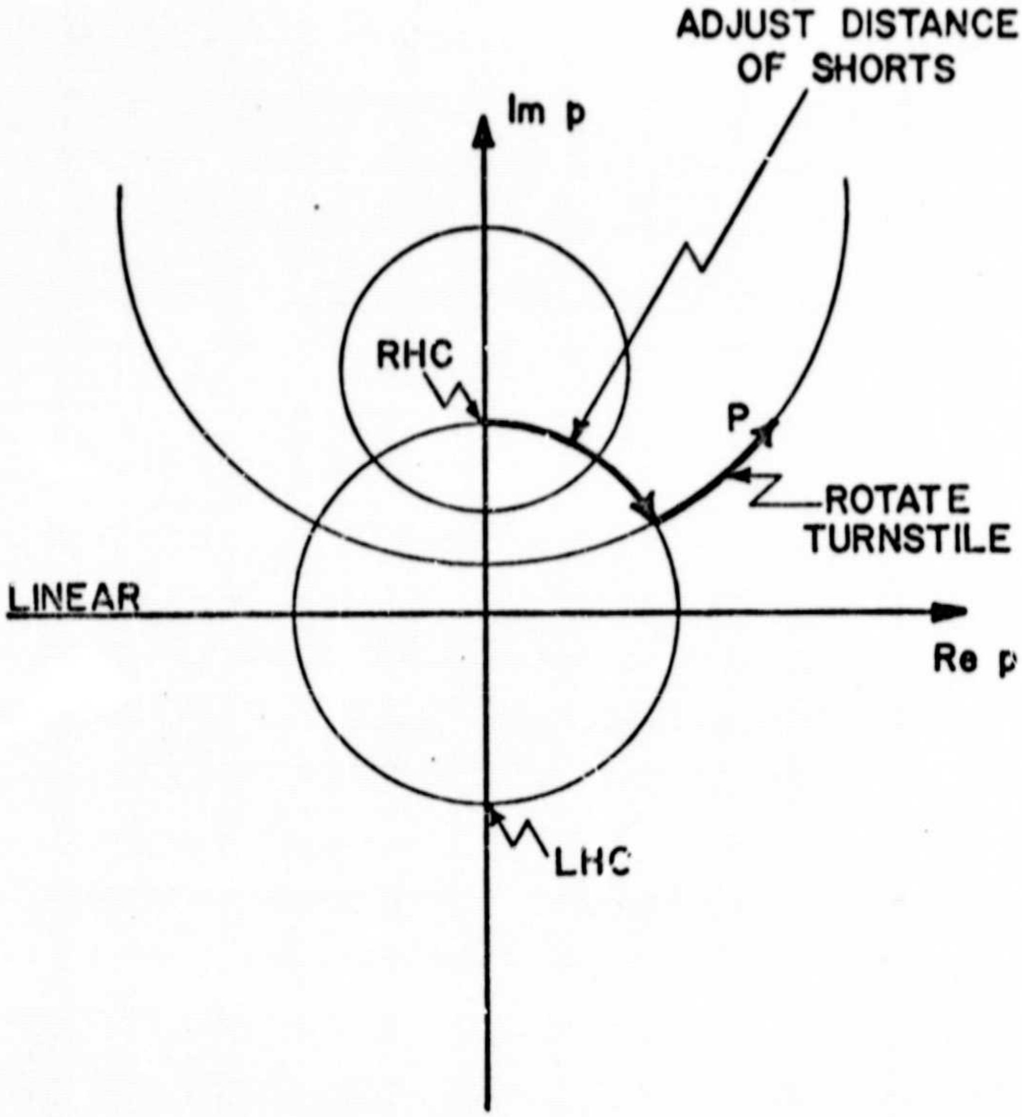

FIGURE 2 THE COMPLEX POLARIZATION PLANE

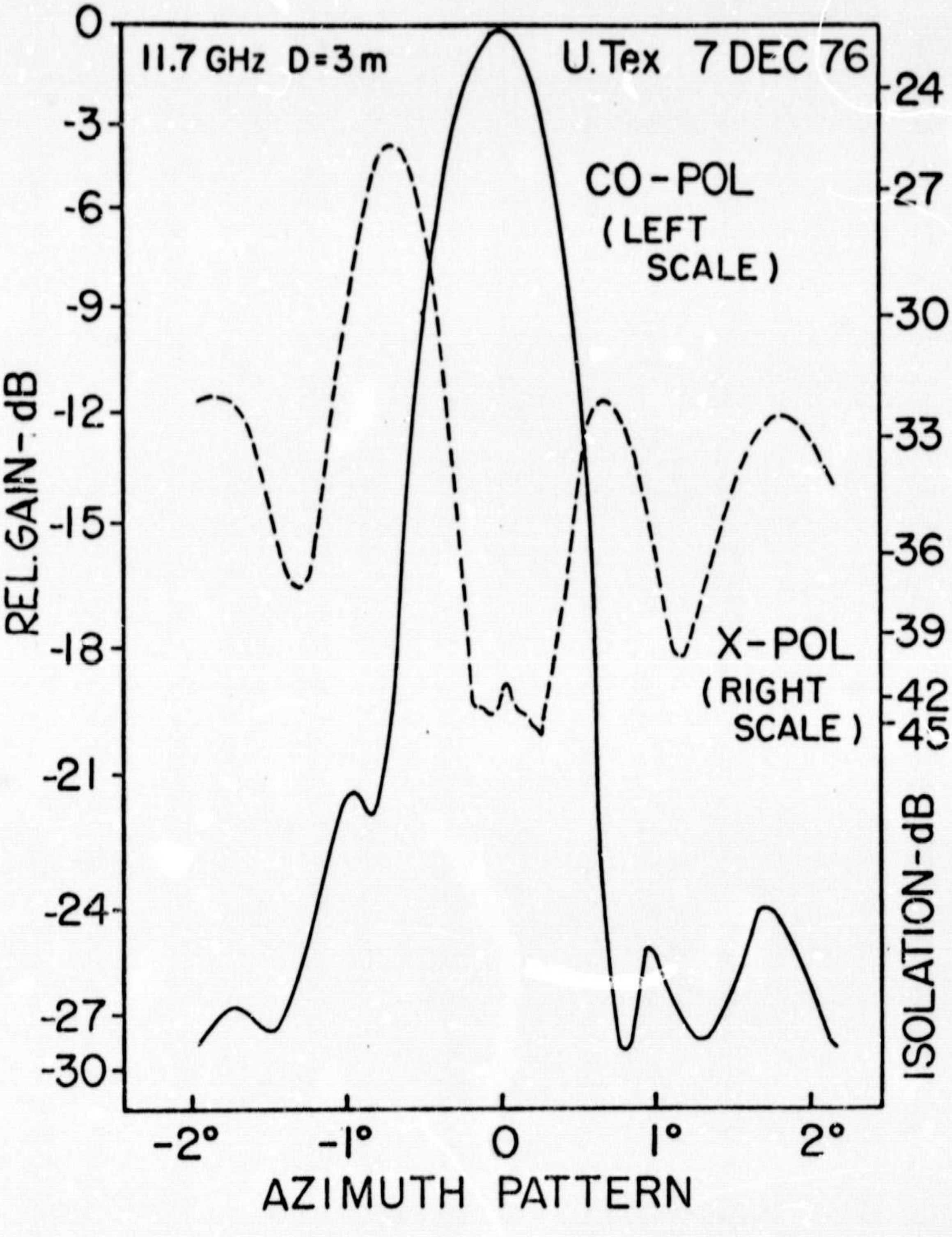

FIGURE 3 AZIMUTH ANTENNA PATTERN

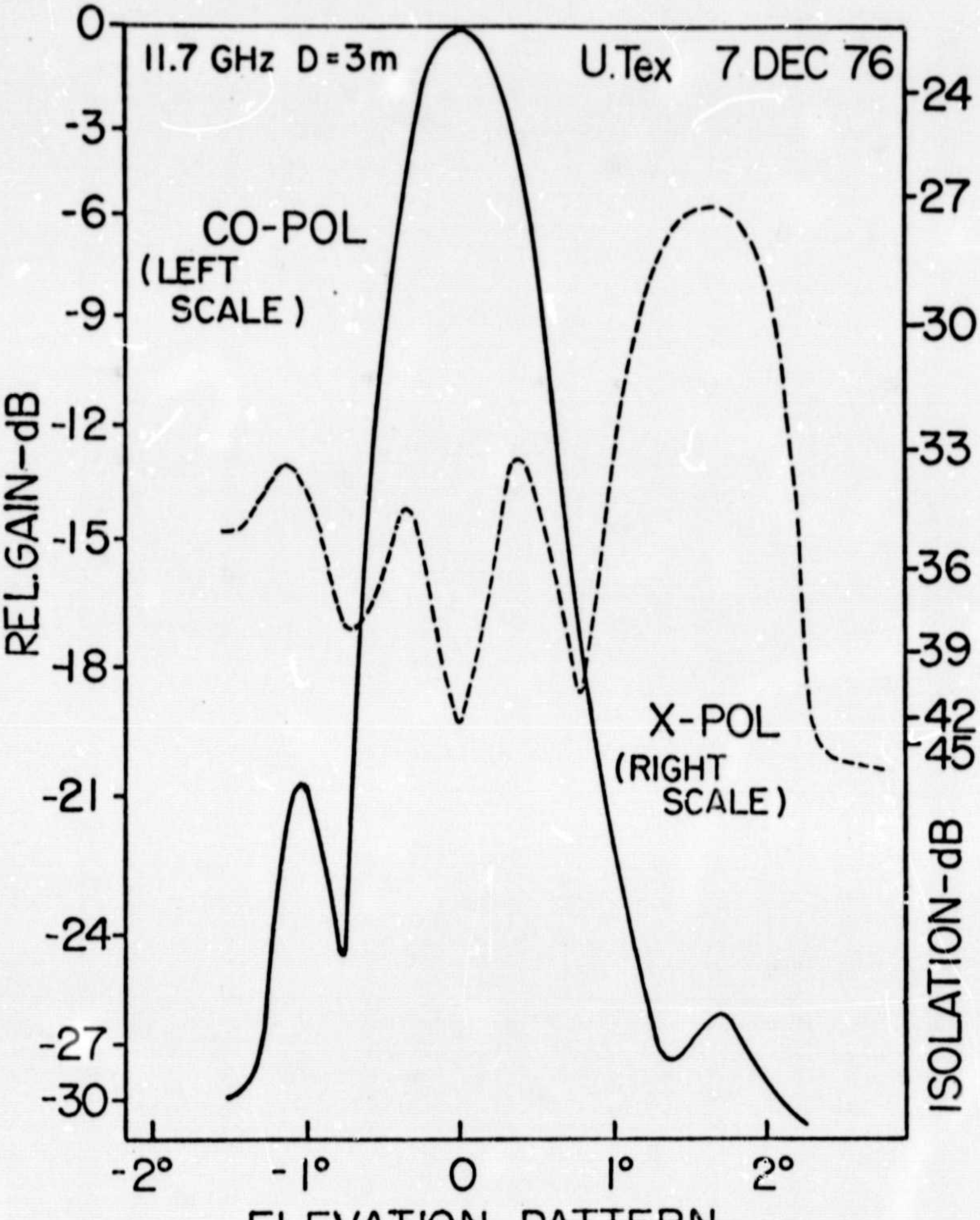

FIGURE 4 ELEVATION ANTENNA PATTERN

The antenna has a prime focus feed (turnstile). A 30 cm long aluminum cylinder with 23.5 cm diameter is supported by a tripod at the focus and serves as universal receiver box.

C. Dual Channel Receiver

Figure 5 is a simplified block diagram of the RF front end. The two orthogonally polarized antenna outputs are connected through waveguide switches to two mixer-preamplifier assemblies. The local oscillator is a phase locked signal source. Its 11.65 GHz output is derived from a stable 107.8 MHz crystal oscillator. Isolators in the local oscillator path preserve high isolation between the two channels. The resulting 54 MHz IF signals are processed in the backend housed in a building adjacent to the antenna. From there an 11.7 GHz calibration signal is fed through coaxial cable to the front end. 99 percent of the calibration signal can be directed into the co-polarized channel and 1 percent can be switched into the cross-polarized channel.

The backend is a modified Martin Marietta phase locked loop receiver. It was built for the ATS-5 program and has also been used for the ATS-6 experiments. The 54 MHz IF signals are bandpass filtered, amplified and with a 44 MHz VCO mixed to 10 MHz in the Martin Marietta receiver. The operation of this receiver has been thoroughly described in the literature (Martin Marietta, 1969). The stronger co-polarized signal is used to lock the receiver up. The co- and cross-polarized signal channels have noise bandwidths of 100 and 20 Hz, respectively. The receiver stays locked to

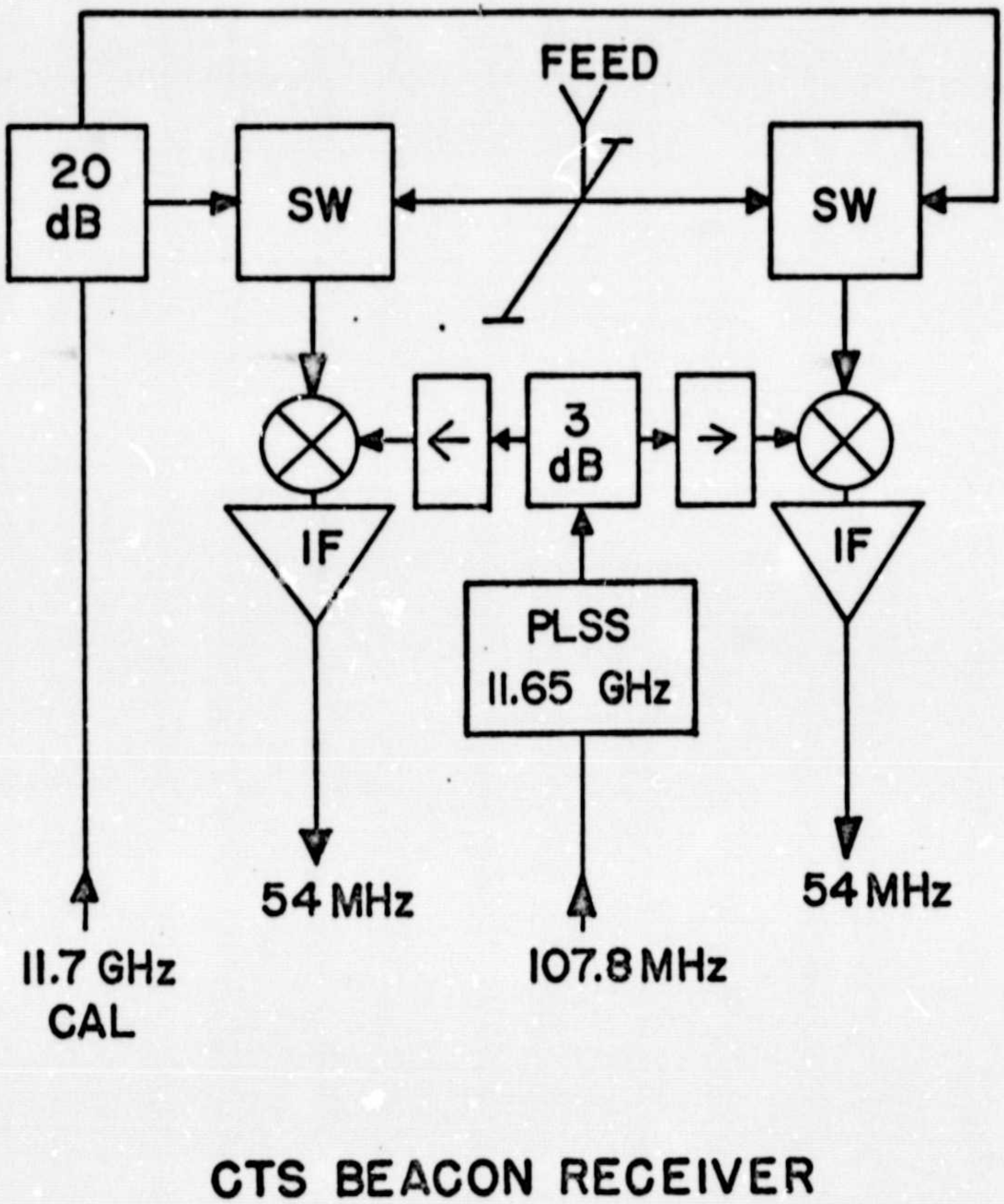

FIGURE 5 FRONT END BLOCK DIAGRAM

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the beacon for fades of over 30 dB. Clear air isolation between channels exceeds 40 dB. Logarithmic outputs of the signal strengths in each channel are recorded on a dual pen chart recorder.

D. Calibration

The output of a phase locked signal source at 11.7 GHz is fed through a calibrated attenuator into the front end assembly where the larger output from a 20 dB directional coupler can be switched into the co-polarized channel and the smaller output into the cross-polarized one. The difference in power level to the two receivers in the calibration mode has been measured to be 20.5 dB. By stepping the calibrated attenuator over a total range of about 30 dB a scale is created on the recording chart which can then be used to determine the relative power levels in the co- and cross-polarized channels. This calibration is performed at regular intervals (about once a week) and whenever attenuation or cross-polarization events occur.

E. Operation

The receivers were operated on a 24 hour per day basis starting 12 June 1976 until the beacon transmitter was shut down on 30 August 1976 for the duration of the solar eclipse.

III. Meteorology of Austin

A. Thunderstorm Climatology for Central Texas

High attenuation events were always associated with thunderstorms in the Austin area. The storm climatology is given to help in the interpretation of the attenuation data.

Information on thunderstorms in Central Texas is given in Table I. The frequency of occurrence refers to the mean over a thirty year observational period and was obtained from Local Climotological Data for Austin, Texas. The other information was obtained from Mr. William Hare, Meteorologist in Charge at the National Weather Service Meteorological Observatory, Radar Center, Hondo, Texas. Data obtained from the radar at Hondo (which includes Austin in the scope area) for the two years this site has been in operation were used. These data should be fairly representative of the Austin area. Cloud (thunderstorm) tops are given in kilometers above mean-sea-level, the translational speed of the individual rain cells is given in km/hr, and the direction of movement of the rain cells is given as the direction from true north from which the cell is moving. It should be pointed out that when the showers are arranged in a line (a squall line) as they frequently are in the spring (March through May) the line usually moves from 300° to 310° (i.e. from the northwest). The individual shower cells within the line, however, move in the direction as indicated in the Table.

Thunderstorm frequency is bimodal, as shown in the Table. May and August have the highest observed mean frequencies (though the standard deviation is very large throughout the year). Maximum cloud tops occur almost concurrently with maximum frequency. Translational speed of individual cells is at a maximum in early spring (March) when mean wind speeds within the troposphere at this location are at a maximum. Minimum

Table I

MEAN VALUES OF THUNDERSTORM PARAMETERS

FOR CENTRAL TEXAS BY MONTH OF YEAR

Month	Frequency of Occurrence	Height of Cloud Tops km	Cell Speed (km/hr)	Direction of Movement (degrees)
Jan	1	8.5	46	240
Feb	2	9.1	56	250
Mar	3	11.6	65	270
Apr	5	12.2	56	250
May	7	12.8	46	240
Jun	4	10.7	37	180
July	4	9.8	28	170
Aug	5	9.8	28	150
Sept	4	12.2	46	230
Oct	3	11.6	46	230
Nov	2	9.1	46	240
Dec	1	8.5	46	240

speeds are observed in late summer. The direction of movement of individual cells has a strong southwesterly to westerly component most of the year, except in the summertime when cells move from the south (June) to southeast (August).

B. Meteorology for 12 June 1976 - 30 August 1976

The total rainfall for 12 June - 30 August 1976 was 112 mm. During this 80 day period there were 11 days with more than 2.5 mm total precipitation. The fraction of time the rainrate exceeded values between 2 and 200 mm/hr is shown in Fig. 6 for this time period. The data are based on one standard 20 cm tipping bucket raingauge located at the receiving site.

IV. Results of the Attenuation and Cross-polarization Isolation Measurements

The chart records were digitized at one minute intervals for all periods of data events. These are defined by either the attenuation exceeding 1 dB or the cross-polarization isolation reduced below 35 dB. Cross-polarization isolation (CPI) is defined by

$$\mathrm{CPI} = \frac{\text{Power received in the co-polarized channel}}{\text{Power received in the cross-polarized channel}}$$

The most severe data event occurred on 26 August 1976. A time plot of the rainrate, attenuation and isolation for that event is shown in Fig. 7. The raingauge recorded a peak rainrate of over 250 mm/hr. While tipping bucket gauges are not very accurate at such high rates they nevertheless

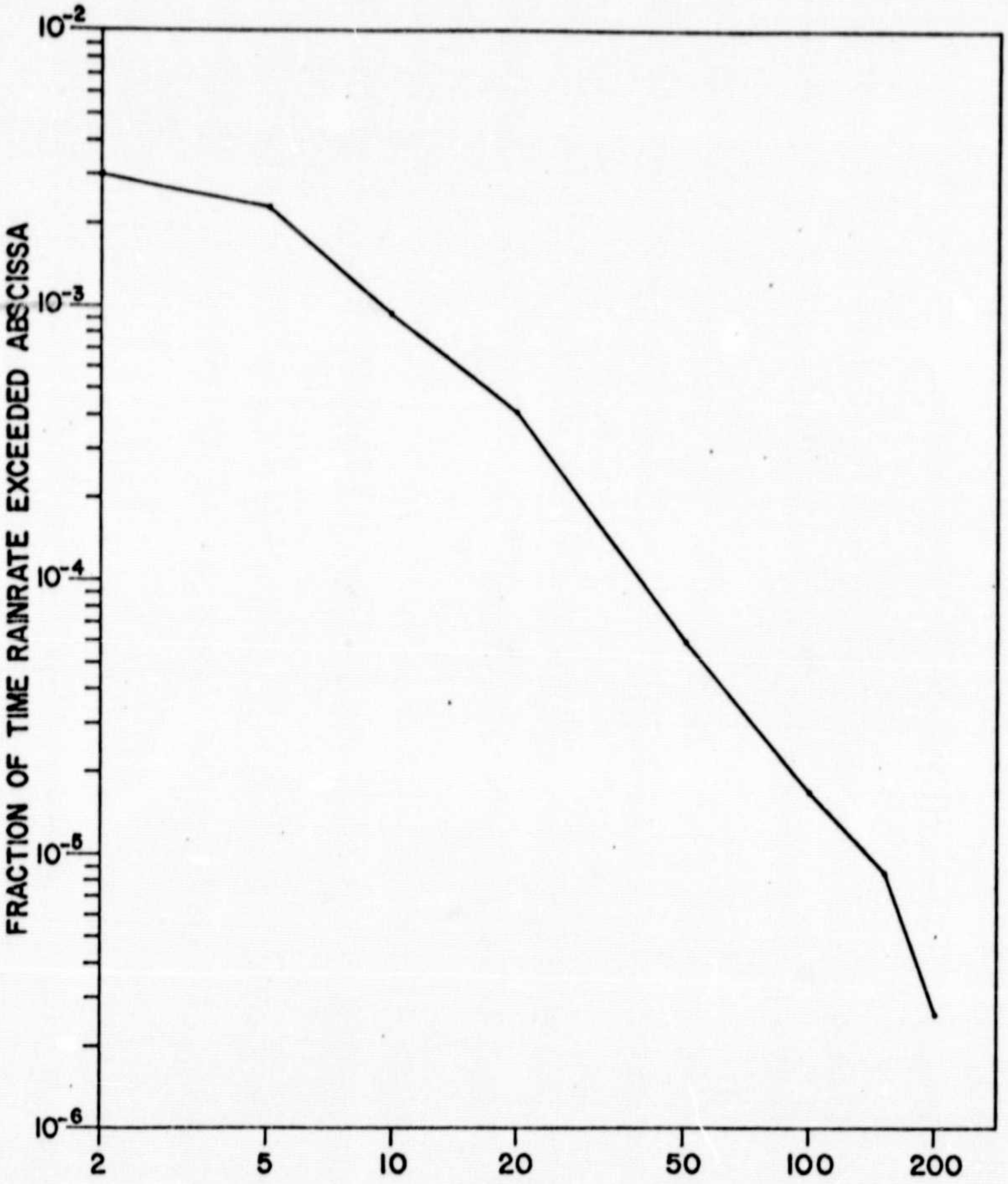

FIGURE 6 RAIN RATE EXCEEDENCE PLOT

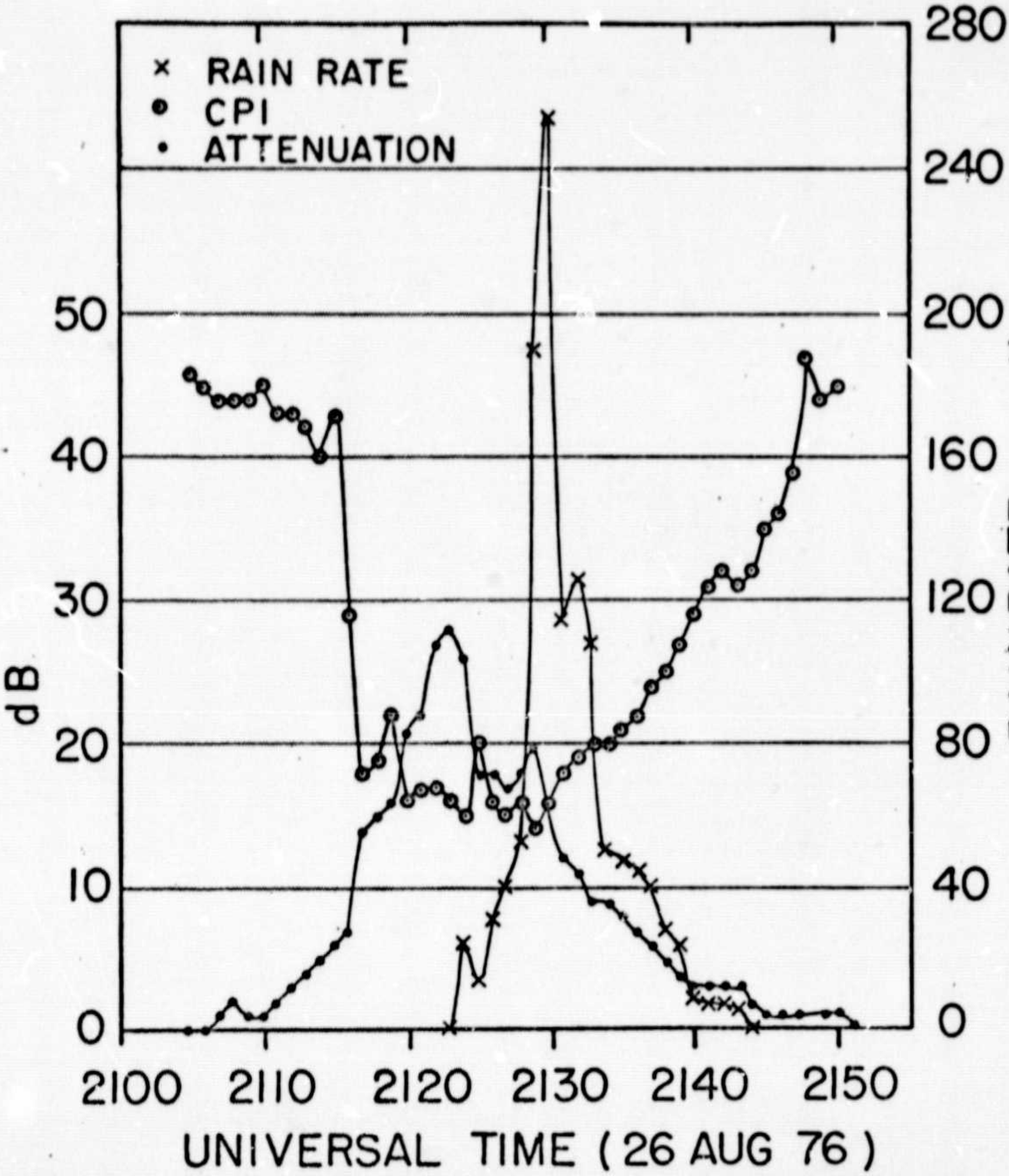

FIGURE 7 DATA FOR THUNDERSTORM OF 26 AUG 1976

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give an indication of the severity of the downpour. During this storm isolation was reduced to 14 dB and the maximum attenuation was 28 dB.

In Fig. 8 the isolation is plotted versus the attenuation A for this event. A logarithmic curve fit resulted in a relationship of

$$CPI = 36.8 - 15.7 \log A$$

with a coefficient of determination $r^2 = .90$. Also indicated in the graph is the time sequence of the measured points. It is interesting to note that the attenuation at first increases without much deterioration of the isolation.

Figures 9, 10 and 11 give isolation versus attenuation for three other rainstorms. Logarithmic curve fits were made to describe the relation. The results are

$CPI - 34 \quad - 10.6 \log A$ for 15/16 June 76

$CPI = 36.6 - 13.8 \log A$ for 19 June 76

and $CPI = 43 \quad - 24.2 \log A$ for 25 July 76.

All the 1 minute samples of data events collected have been plotted in Fig. 12. Note that by the way data events were defined periods with attenuation less than 1 dB and isolation better than 35 dB are not usually digitized. A least squares fit for all data with $A \geq 2$ dB resulted in

$$CPI = 38.9 - 17.4 \log A.$$

Added in the plot are theoretically derived curves for 17 and 30 GHz. They were calculated by applying a point matching procedure to drop shapes of rain falling in still air and assuming a statistical distribution of canting

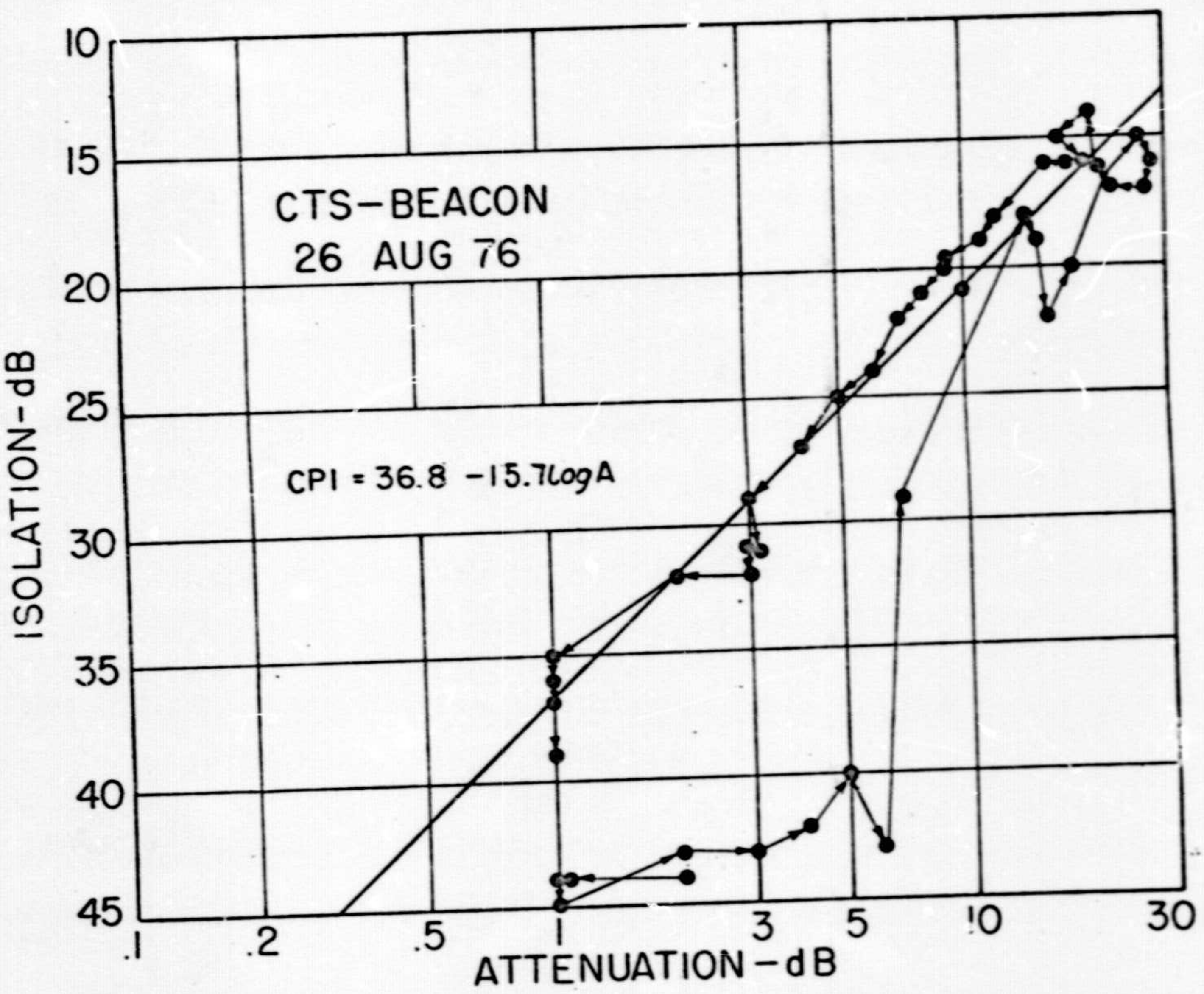

FIGURE 8 ISOLATION VS. ATTENUATION, 26 AUG 1976

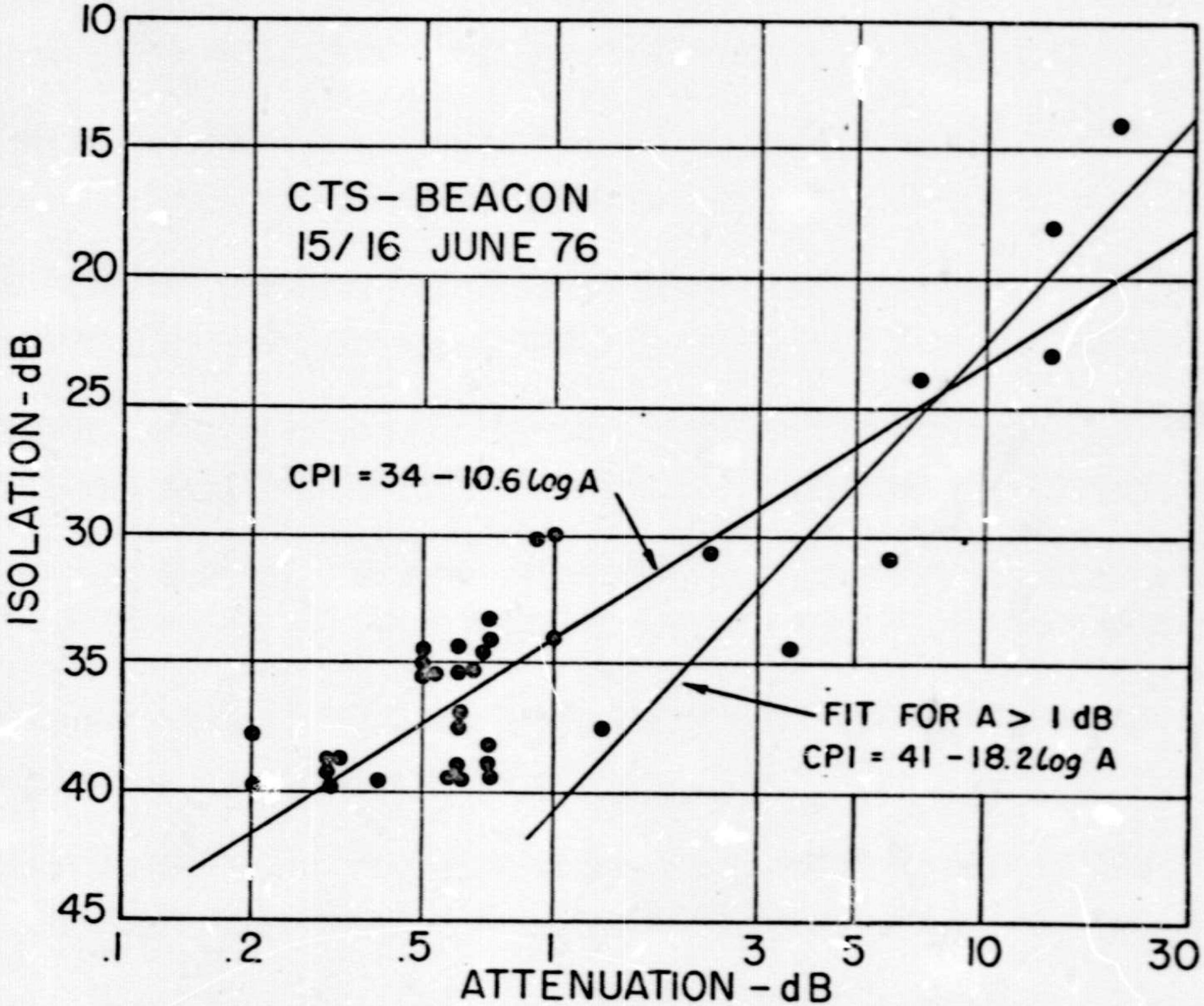

FIGURE 9 ISOLATION VS. ATTENUATION, 15/16 JUNE 1976

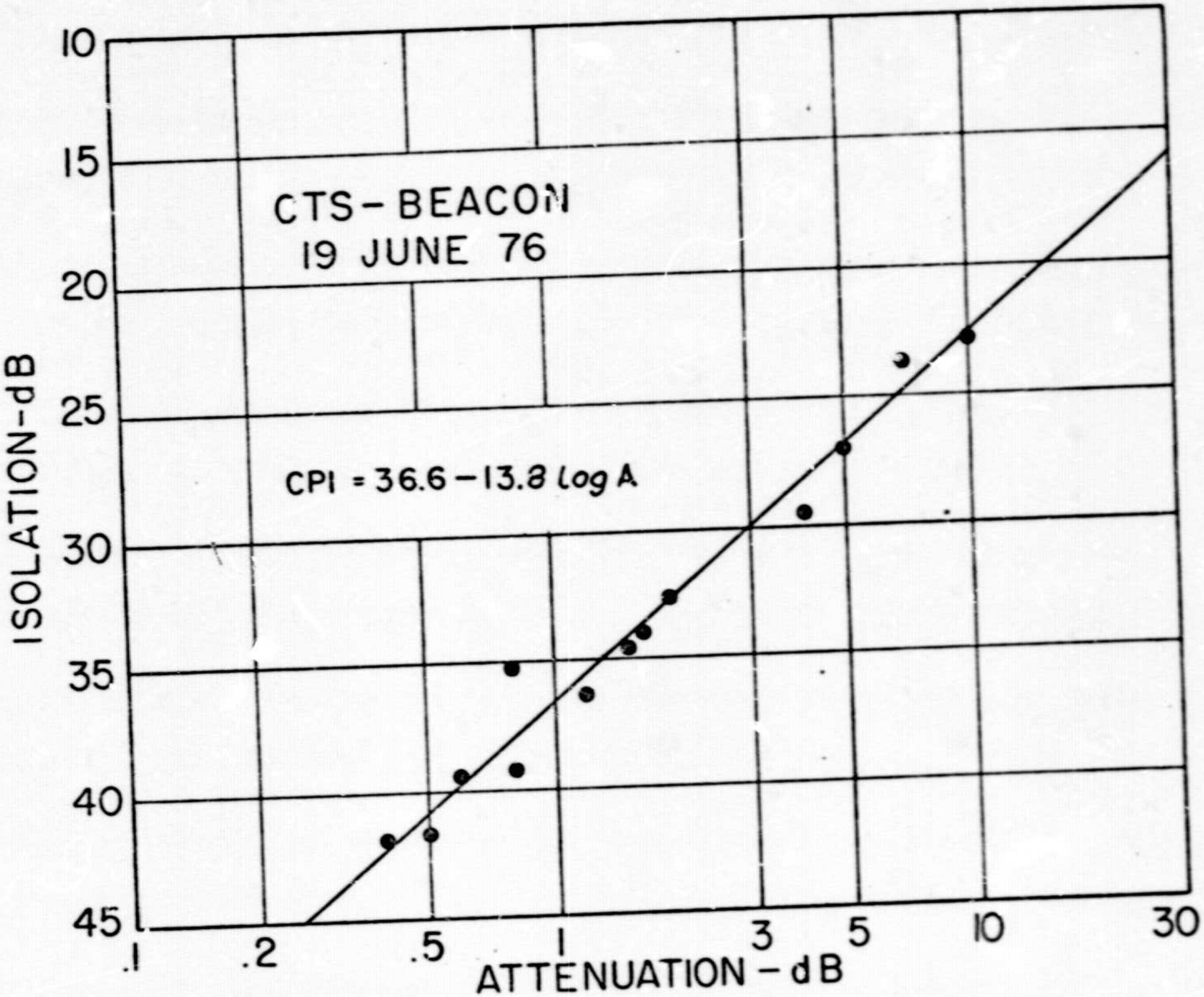

FIGURE 10 ISOLATION VS. ATTENUATION, 19 JUNE 1976

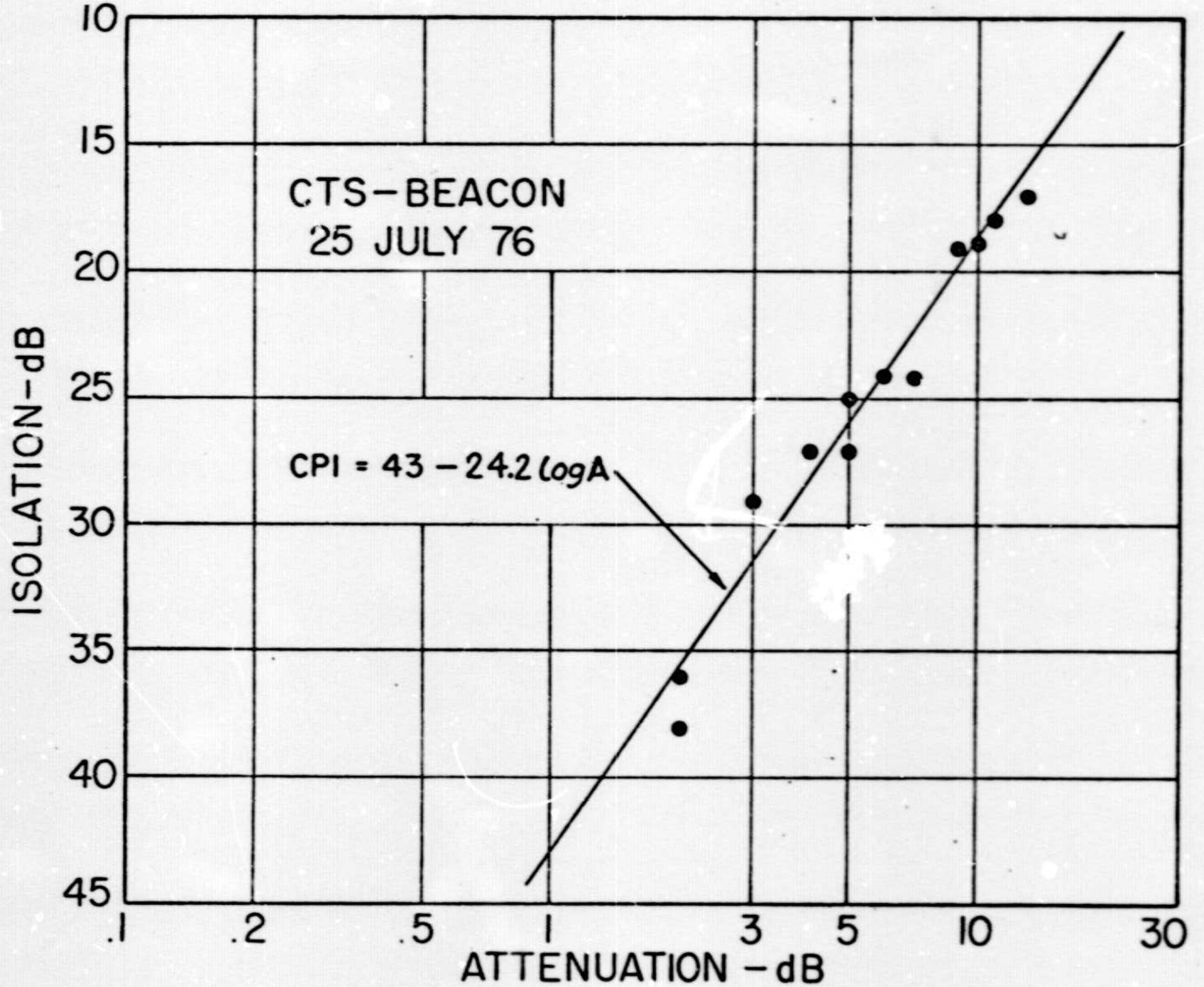

FIGURE 11 ISOLATION VS. ATTENUATION, 25 JULY 1976

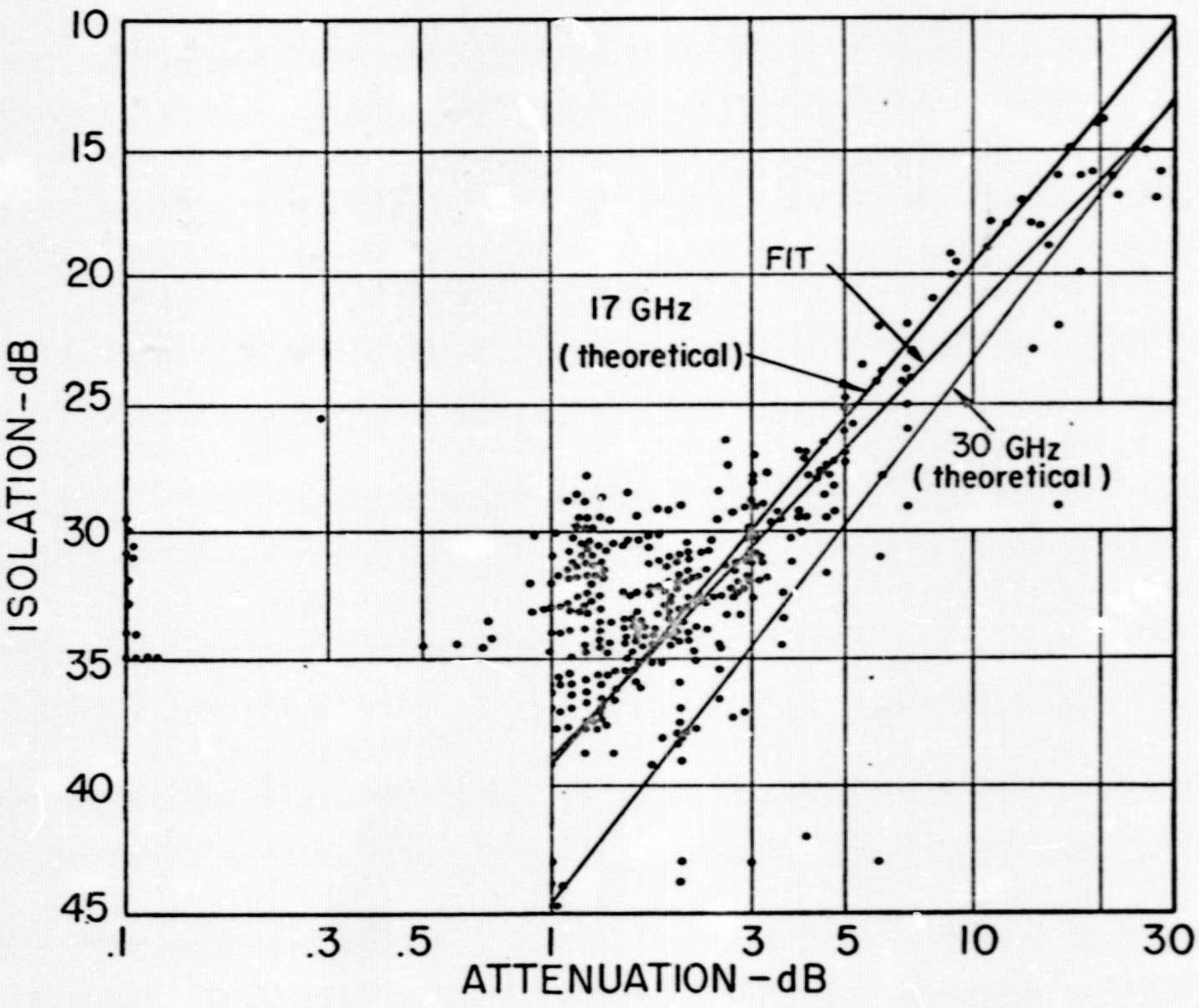

FIGURE 12 ISOLATION VS. ATTENUATION, 12 JUNE 1976 - 30 AUG 1976

angles of the drops in the rain volume (Vogel, 1973). It is apparent that at low attenuations (<3 dB) the logarithmic fit of the points is deteriorated, with the cross-polarization isolation generally less than predicted. A contributing factor to this behavior is the anisotropic phaseshift introduced to the wave by frozen particles in the atmosphere, resulting in a change of polarization with very little accompanying attenuation. Such behavior was generally observed in conjunction with thunderstorms which are an indication of ice formation. On these occasions isolation was frequently reduced to about 30 dB, but never below 25 dB, without any noticeable change of the co-polarized power received.

Figure 13 shows the chart record for one of these events. It is obvious that over 15 dB changes of the cross-polarization isolation within a few seconds are not correlated to the attenuation of the co-polarized signal. When attenuation finally occurred the character of the cross-polarization fluctuations changed.

The cumulative time fraction for which the isolation was reduced below a certain level together with the time fraction for which the attenuation exceeded a certain value has been plotted in Fig. 14 for the measurement period. It should be emphasized that these curves are based on only 80 days of measurements. Therefore the extrapolation to yearly statistics, as indicated on the righthand margin of the graph, should be considered only a rough estimate.

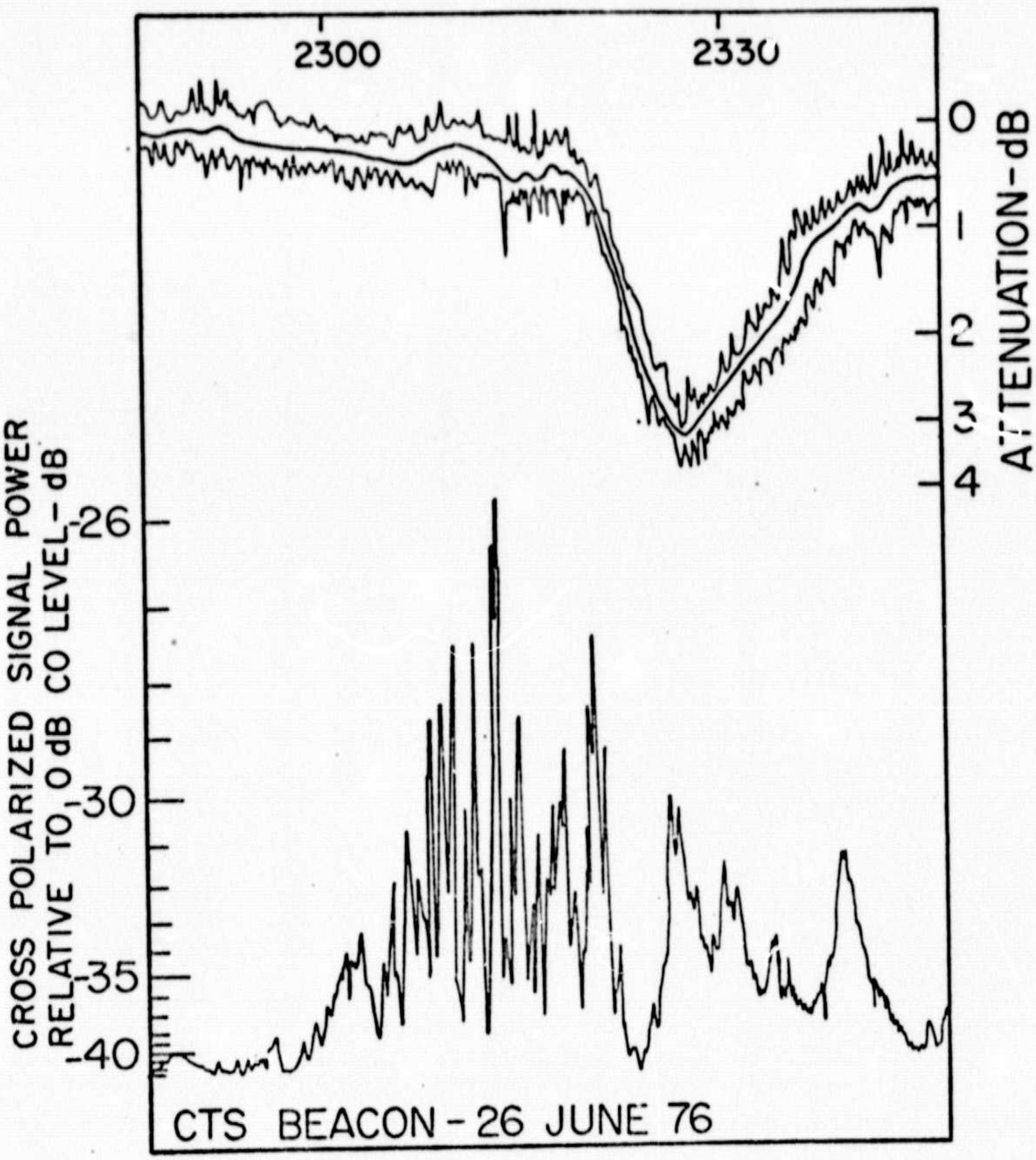

FIGURE 13 CHART RECORD FOR ICE DEPOLARIZATION

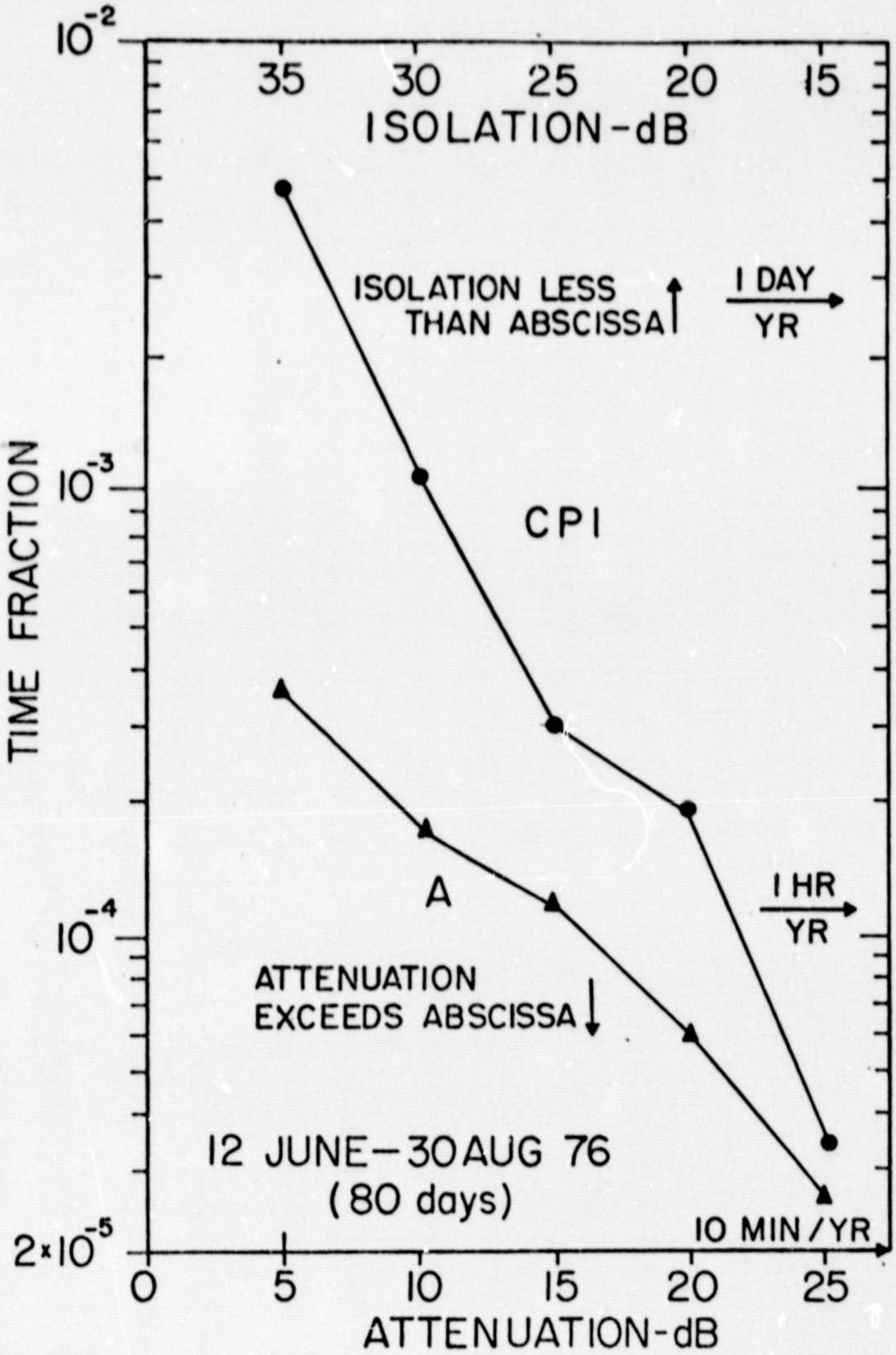

FIGURE 14 EXCEEDENCE PLOT FOR ATTENUATION AND CROSS-POLARIZATION ISOLATION

A frequency reuse system with a 27 dB isolation requirement would have not been fully operational for .05 percent of the time at this location during the indicated 80 days. For this outage time the required fade margin with less than 5 dB would have been no severe constraint. A frequency reuse system with a 10 dB fade margin and a 27 dB isolation requirement would be limited by the loss of isolation. Applying polarization adaption methods could improve isolation and make attenuation the limiting factor. Besides the gain in reliability this would have the advantage of making the system more predictable, since attenuation outages can be determined if rain intensity statistics are known, whereas depolarization outages can not (Crane, 1977).

V. Conclusions

The depolarization of electromagnetic waves by rain or ice in the atmosphere presents a limitation to the reliability of frequency reuse systems operating at 11.7 GHz. Cross-polarization events can be divided into two categories. (1) Low attenuation anisotropic phaseshift through ice clouds causes depolarization to about 25 dB CPI. (2) Propagation through rain couples depolarization and attenuation with a relationship approximated by

$$CPI = a - b \log A$$

where CPI and A are cross-polarization isolation and attenuation in dB. For circular polarization the constants a and b take values of near 39 and 18. Therefore in systems that employ no depolarization compensation techniques the fade margin and required isolation can not be specified independently. For the data presented here a realistic system with a fade margin of 10 dB and an isolation of at least 27 dB would have been limited in its operation most seriously by depolarization.

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